

Cold hibernated elastic memory (CHEM) self-deployable structures

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ABSTRACT

Experiments have confirmed the feasibility of an innovative, new class of very simple, reliable, low mass, low packaging volume, and low-cost self-deployable structures for space and commercial applications. The concept called “cold hibernated elastic memory” (CHEM) utilizes shape memory polymers (SMP) in open cellular (foam) structures. The SMP foam materials are under development by the Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). The CHEM structures are described here and their major advantages are identified over other expandable/deployable structures. In preliminary proof-of-concept investigation conducted on SMP foams, all evaluation/test results were very encouraging and confirmed the basic characteristics of CHEM structures. The main objective of this program is to develop and validate the CHEM structure technology for most promising space applications. However, possible terrestrial commercial applications are also anticipated and described in this paper as well.

Keywords: expandable structures, shape memory polymers, open cellular structures, glass transition temperature T_g , glassy and rubbery states

1. INTRODUCTION

Presently, a modern spacecraft is undergoing revolutionary change towards higher capability at low-cost and small size. It is envisioned that eventually the spacecraft avionics will shrink to the size of a single microchip. However, there are some spacecraft subsystems that resist miniaturization. Space antennas require large sizes to deliver high data rates or in case of mobile communication satellites provide simultaneous multiple user access increasing profits, large size sensors are often dictated by the physics of the specific application, etc. All these science, commercial and National Aeronautics and Space Administration (NASA) or Department of Defense (DoD) applications call for large expandable, deployable space structures. The space community is getting ready for a new spacecraft architecture: a spacecraft that is Lilliputian at launch but deploys huge apertures and appendages when in space.

Unfortunately, presently used mechanically deployable structures are heavy, complex, not highly reliable, expensive, and not stowed volume efficient. In order to fit a modern spacecraft architecture, the space deployable structure also should go through revolutionary changes towards lower weight and packaging volume. Therefore, one of the major efforts at NASA and DoD has been to develop expandable structures characterized by low mass and small launch volume to be used in small, low-cost missions. As a result, space inflatable structures have emerged just a few years ago. A cold hibernated elastic memory (CHEM) structure is the most recent result of the quest for simple, reliable and low-cost expandable structures. It represents the next generation self-deployable structure and intends to be supplemental to space inflatable structure technology.

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2. CHEM STRUCTURE DESCRIPTION

The CHEM concept utilizes shape memory polymers (SMP) in open cellular (foam) structures ¹. The SMP materials have been developed by Mitsubishi Heavy Industries, Nagoya R & D Center, Japan in the last 10 years. They offer unique properties for a variety of applications. These materials are polyurethane-based thermoplastic polymers with wide glass transition temperature T_g range. They are unique because of exhibiting large changes in elastic modulus E above and below the T_g . A large amount of inelastic strain (up to 400%) may be recovered by heating. The reversible change in the elastic modulus between the glassy and rubbery states of the polymers can be as high as 500 times. In addition, these materials also have high damping properties in transition temperature range and large temperature-dependence on gas permeability. Mechanical and chemical properties, durability and moldability are the same as in conventional polyurethanes. The material's shape memory function allows repeated shape changes and shape retention. This phenomenon is explained on the basis of molecular structure and molecular movements ^{2, 3, 4, 5}. The molecular chains can undergo micro-Brownian movement above the T_g (rubbery state) when the elastic modulus of the polymer material is low. In the rubbery state, the material can be easily deformed by application of external force, and the molecular chains can be oriented in the direction of the tension. When the temperature is lowered below the T_g and the deformation remains constant, the micro-Brownian motion will be frozen and the chain orientation and deformation will be fixed. When the material is heated above the T_g , the micro-Brownian movement starts again, the molecular chains lose their orientation and the material will recover its original shape. In this case, the shape-recovery function of the material requires crosslinking or partial crystallization.

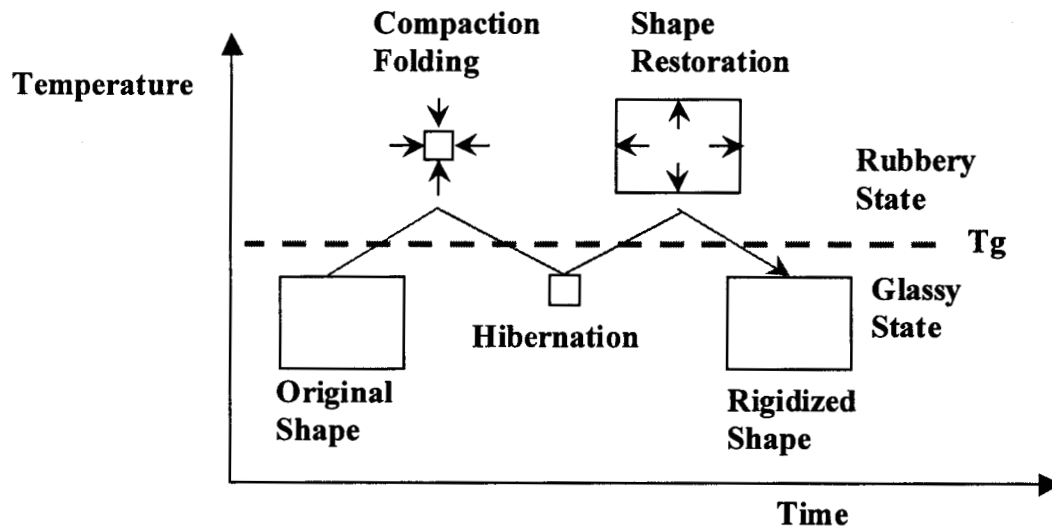


Figure 1: CHEM processing cycle

The CHEM concept is illustrated in Figure 1. In this concept the structures of any shape such as rods, tubes, wheels, boards, chassis, packages, tanks etc made of SMP foams are compacted to very small volumes in a flexible state above the glass-transition temperature T_g and later cooled below T_g to a glassy state. When the stowed structure is frozen, the external compacting forces are removed and the part can be stowed in a cold hibernated state for an unlimited time below T_g . A compacted part can be heated above T_g to a flexible state and the original shape will be precisely restored by simultaneous foam's elastic recovery and shape memory polymer effect. A fully deployed structure can be rigidized by cooling below T_g to a glassy state. Once deployed and rigidized, a part could be heated and recompact. In principle, there should be no limit to the achievable number of compaction/deployment/rigidization cycles. The stowed and deployed CHEM structures are shown in Figure 2 ⁶.

The attractiveness of the CHEM structure is the wide range of T_g that can be selected from -70°C to $+70^{\circ}\text{C}$ and higher, resulting in a variety of potential space and terrestrial applications. In these applications, the T_g of CHEM structure should be just above the maximum ambient temperature to keep the part in the glassy state most of the time. For example, for the Mars Pathfinder mission the T_g of CHEM structure should be close to 0°C , on the other hand for warmer terrestrial applications it should be 50°C and higher.

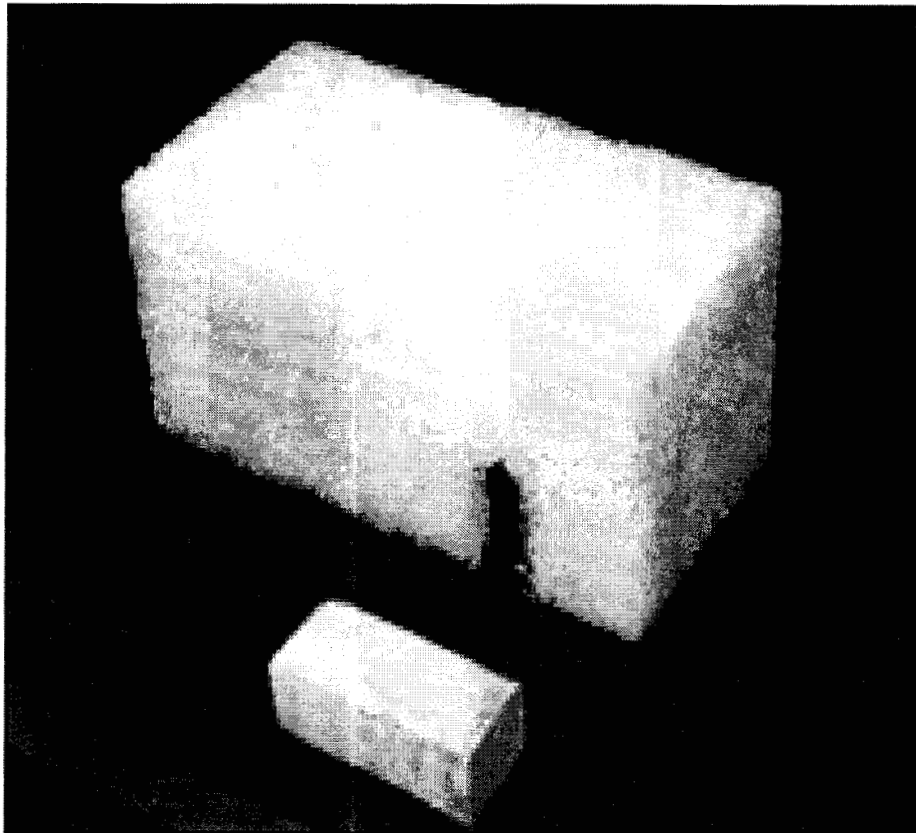


Figure 2: Stowed and deployed CHEM structures

The main advantage of CHEM structures over conventional polymer foams is that high total compressive strain, both elastic and plastic, is recovered without any compression set. Thus, a higher full/stowed volume ratio is accomplished in rubbery state and the original shapes are recovered with higher accuracy after cold hibernation stage. In addition, very high ratios of elastic modulus E below T_g to E above T_g (up to 500 for solid SMP) allow to keep the original shape in stowed, hibernated condition without external compacting forces for an unlimited time below T_g . Furthermore, a small transition temperature range for full transformation from glassy to rubbery state reduces the heat consumption during deployment (shape restoration)

3. BENEFITS AND APPLICATIONS

3.1. Advantages/disadvantages

The CHEM structure represents a new class of low mass, low packaging volume and low-cost self-deployable structures for space and commercial applications. A long line of CHEM structure's major advantages are listed below:

- *Low mass.* Polymer foam structure assures lightweight: almost 2 orders of magnitude lighter than aluminum.
- *Low stowage volume.* Incorporation of shape memory polymers in open cellular structure affirms high compressibility and full/stowed volume ratios.
- *High reliability.* No deployment mechanisms, controls nor inflation systems etc.
- *Low cost/quick technology development.* Already developed solid shape memory polymers are inexpensive. Short time for technology development is anticipated.
- *Self-deployable.* Precision deployment by elastic recovery and shape memory of SMP foam.
- *Simplicity.* Simple deployment and rigidization. A structural & thermal isotropy behavior results in predictable thermal & temporal dimensional stability.
- *High dynamic damping.* Foam acts like a structure composed of thousands of interconnected springs.
- *Clean deployment and rigidization.* Deployment by elastic recovery & shape memory effects and rigidization by transition from rubbery to glassy state assure clean, contamination-free environment.
- *None long-term stowage or storage effects.* CHEM structures can be stowed in glassy state for an unlimited time without any compression set. They offer indefinite storage/shelf life in rubbery state compared with restricted storage or refrigeration of other polymers.
- *Ease of fabrication.* Good machinability in glassy and rubbery states. Cutting and shaping possible by conventional & computer numerically controlled (CNC) machining.
- *Impact and radiation resistant.* Polyurethane-based CHEM foams belong to preferred class of space radiation resistance materials. They can effectively absorb the energy of impact or of forces generated by deceleration without creating high damaging stresses.
- *Good thermal and electrical insulator.* Very low thermal and electrical conductivity.

The disadvantage of CHEM structure is that heat energy is needed for deployment. However, the natural heat sources are considered to be utilized and the studies/proof-of-concept experiments are planned to be conducted.

3.2. Potential Applications

CHEM provides NASA/JPL a robust, innovative self-deployable structure with significantly higher reliability, lower cost and simplicity over other expandable/deployable structures to be used on many future space missions in Earth and Space Science Programs. Myriad CHEM applications are anticipated for space robotics and other support structures for telecommunication, power, sensing, thermal control, impact and radiation protection subsystems as well as for space habitats. The potential space applications are listed below. This list is by no means meant to be exhaustive.

- Support structures for telecommunication subsystems such as struts, beams etc.
- Robotics: rover subsystems such as wheels, chassis, insulation box, masts.
- Low frequency parabolic antennas.
- Power: solar array deployment device.
- Sensing systems: radar structure.
- Thermal control: insulation shields.
- In-situ propellant production: tanks, containers etc.
- Space habitats: shelters, hangars etc.
- Space electronics: insulation, boards.
- Space Station/Trans Habs: shells, shields, airlocks etc.

Although space community will be the major beneficiary, a lot of potential commercial applications are also foreseen for the earth environment. The CHEM concept could be applied to shelters, hangars, camping tents or outdoor furniture to mention just a few. Such articles could be made of CHEM foam with a T_g slightly above the highest outdoor summer temperature.

The CHEM parts can be transported and stored in small packages then expanded by heating at the outdoor site. After expansion, CHEM parts will be allowed to cool to ambient temperature below their T_g , so that they would become rigid as needed for use.

4. CHEM TECHNOLOGY DEVELOPMENT

The CHEM Structure Technology Development Program was established at JPL in November 1997. The main objective of this program is to develop and validate the CHEM self-deployable structure technology for selected space applications. These technology development activities are the collaborative efforts between JPL and Nagoya R & D Center, Mitsubishi Heavy Industries LTD (MHI). MHI is responsible for development of the shape memory polymer (SMP) foam materials for CHEM concept. JPL works with MHI to make SMP foams workable for CHEM self-deployable structure applications.

The CHEM structure technology was designed to be developed in 3 phases: Phase 1: Proof-of-CHEM Concept (already completed), Phase 2: Characterization and sub-scale CHEM application development (present activities) and Phase 3: Full-scale CHEM application technology ground validation (future activities). The proof-of-CHEM concept investigation results as well as present and future activities will be briefly described in the following sections.

4.1. Proof-of-CHEM Concept Investigation

The objective of Phase 1 was to build small structural models of possible space applications and demonstrate the basics of CHEM concept. Several of these structural models are shown in Figure 3.

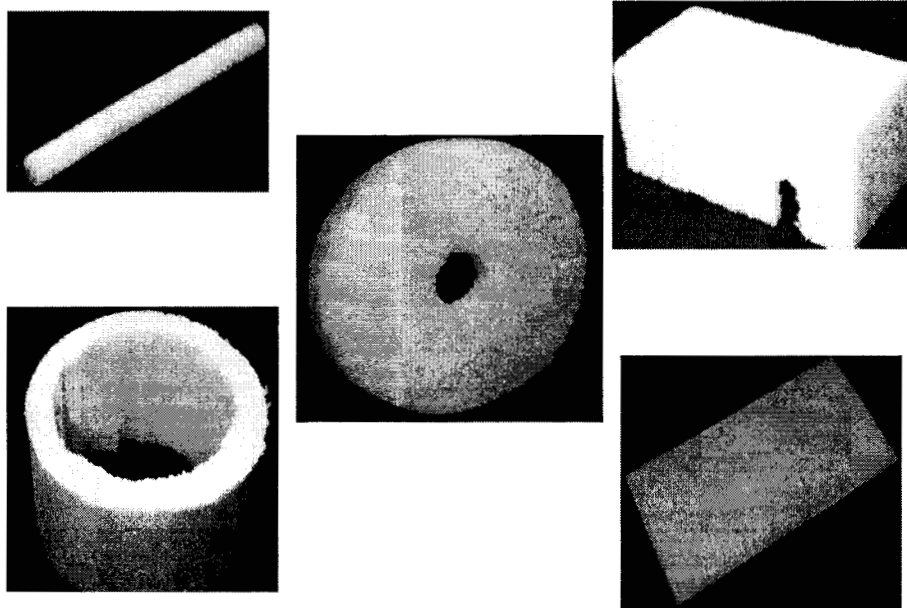


Figure 3: CHEM structural models

For convenience and simplicity, MHI developed and submitted to JPL a shape memory polymer foam designated MF 5520 for earth environment demonstration with a T_g of 63°C . Therefore, our CHEM structural models were fabricated and machined at ambient temperature in rigid state, compacted and/or folded above 63°C in flexible state, stowed in a cold hibernated state in ambient environment, deployed by heating above 63°C and rigidized by cooling again to room temperature. More property data of MF 5520 and another sample M-18G is displayed in Table 1.

Table 1: Properties of SMP foams.

Properties	MF 5520	M-18G
Density (g/cm ³)	0.032	0.049
T _g (°C)	63	- 4
E _g below T _g (MPa)	2.69	7.44
E _r above T _g (MPa)	0.064	0.023
E _g / E _r	42	323

During Phase 1 all evaluation and test results were very encouraging ⁷. Moreover, all structural models including rods, tubes, wheels, chassis, boards, tanks demonstrated the basics of CHEM concept such as:

- High full / stowed volume ratios above T_g: up to 40
- Long-term stowage unconstrained in cold hibernated condition: over 1 year and continued
- Deployment when heating above T_g
- Precision original shape restoration after long stowage.
- Rigidization of original shape when cooling below T_g.

In addition, a shape memory polymer foam designated M-18G was developed specifically for Mars applications. Its elastic modulus was increased 3 times by chopped fiberglass reinforcement (see Table 1). This foam material as well as other SMP foam materials under development for Mars exploration will be tested and characterized in detail in Phase 2 of this program.

4.2. Present and Future Activities

Presently Phase 2 is being conducted. The objective is to develop the SMP foams for Mars applications, conduct a comprehensive characterization to generate a property data base, perform thermal & structural analyses and select & build a sub-scale CHEM space application(s). These activities will be completed by the end of year 1999.

The next step will be Phase 3: "Full-scale CHEM application technology development". This phase will consist of the ground prototype demonstration and validation of CHEM structure technology in a simulated space environment. Phase 3 is planned to be completed by the end of year 2000. Subsequently, a meaningful flight experiment will be proposed to demonstrate a system prototype in the space environment.

5. CONCLUSIONS

Experiments have confirmed the feasibility of an innovative, new class of low mass, low packaging volume and low-cost expandable/deployable structures for space and commercial applications. When developed, the cold hibernated elastic memory (CHEM) structure will provide NASA/JPL a revolutionary, next generation self-deployable structure with significantly higher reliability, lower cost and simplicity over other deployable structures to enable many future small and larger space missions. Myriad CHEM applications are anticipated for space robotics and other support structures for telecommunication, power, sensing, thermal control, impact and radiation protection subsystems as well as for space habitats. Although space community will be the major beneficiary, a lot of potential commercial applications are also foreseen for earth environment.

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